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Scenario Analysis of Peak Demand Savings for Commercial Buildings with Thermal Mass in California

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Scenario Analysis of Peak Demand Savings for Commercial Buildings with Thermal Mass in California

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ABSTRACT

This paper reports on the potential impact of demand response (DR) strategies in commercial buildings in California based on the Demand Response Quick Assessment Tool (DRQAT), which uses EnergyPlus simulation prototypes for office and retail buildings. The study describes the potential impact of building size, thermal mass, climate, and DR strategies on demand savings in commercial buildings. Sensitivity analyses are performed to evaluate how these factors influence the demand shift and shed during the peak period. The whole-building peak demand of a commercial building with high thermal mass in a hot climate zone can be reduced by 30% using an optimized demand response strategy. Results are summarized for various simulation scenarios designed to help owners and managers understand the potential savings for demand response deployment. Simulated demand savings under various scenarios were compared to field-measured data in numerous climate zones, allowing calibration of the prototype models. The simulation results are compared to the peak demand data from the Commercial End-Use Survey for commercial buildings in California. On the economic side, a set of electricity rates are used to evaluate the impact of the DR strategies on economic savings for different thermal mass and climate conditions. Our comparison of recent simulation to field test results provides an understanding of the DR potential in commercial buildings.

Introduction

Demand response (DR) is a process of managing customer consumption of electricity in response to supply conditions to reduce electricity costs or improve electrical system reliability. Generally, DR refers to mechanisms used to encourage consumers to reduce peak electricity demand by utilizing demand shifting, shedding, or both. Demand shifting refers to a shift in the demand profile, brought about by consuming electricity at a different time to benefit from time-of-use rates, which can be achieved by utilizing thermal energy storage such as ice storage or building thermal mass. Demand shedding is a temporary reduction of peak electric demand for achieving economic savings.

For this study, we conducted a parametric analysis to assess the impact of building mass, utility rates, climate, economizer operation, central plant size, and thermal comfort on energy and cost savings of a prototypical building using an EnergyPlus simulation model (Zhou et al. 2005). As expected, results indicate pre-cooled heavy mass buildings can achieve larger peak demand savings than light mass buildings. Field tests were conducted to demonstrate the effectiveness of pre-cooling strategies in hot climate zones. Significant peak demand reduction (approximately 20-30%) can be achieved in hot weather. A demand response quick assessment tool – DRQAT – was developed for evaluating DR strategies in commercial buildings. DRQAT is based on EnergyPlus simulations in prototypical buildings (Yin et al. 2010).

Various DR strategies have been modeled and tested in a number of simulation and field studies to demonstrate the potential of building thermal mass for load shifting and peak load reduction (Braun 2003; Braun et al. 2001; Xu et al. 2005). Cheng et al. (2008) stated that peak demand reduction was most strongly impacted by the building's thermal mass level. Xu and Zagreus (2009) studied the potential of pre-cooling for demand limiting in a heavy mass building and a light mass building; the results showed that pre-cooling can be very effective if the building mass is relatively heavy. Results from these studies provide an overview of the range of savings from various zone temperature adjustments.

This paper describes the impact of building size, thermal mess level, weather, and DR strategies on peak demand savings in commercial buildings. This paper studies the impact of three types of DR control strategies: **linear**, **step** and **exponential** temperature reset, on the peak demand reduction in a prototypical commercial building under various scenarios. Zone comfort analyses are also studied to better understand the impact of the DR control strategies on the occupancy comfort in terms of Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) (Fanger 1970).

Description of Prototypical Models

EnergyPlus estimates thermal and ventilation loads and runs an HVAC system simulation simultaneously at each time step. This integrated solution provides a more accurate space temperature prediction, which is crucial for system and plant sizing, occupant comfort and occupant health calculations than was provided by DOE2. Loads calculation in EnergyPlus accounts for thermal mass more thoroughly than DOE2. DOE2 does not fully capture the effect of a wall's thermal mass in the load adjustment module, as illustrated by Hong et al. (2009) who used a prototypical data center model to compare the HVAC simulations between EnergyPlus and DOE-2.2. In another study, a prototypical three-story office building EnergyPlus model was used to understand the impact of electricity rate structures on energy cost savings of pre-cooling control strategies (Morgan and Krarti 2007).

General Information

In this paper, similar to previous studies, a prototypical three-story office building is used as a baseline model for peak demand savings scenario analysis. As shown in Figure 1, the prototypical building model is a three-story building with four perimeter zones and one core zone. The building model is defined to meet the envelope requirement of Title 24-2005 (CEC 2005). The densities and schedules for occupancy, lighting and plug loads are taken to be those of the commercial building models with typical operation developed by Torcellini et al (2008). The HVAC system is a packaged variable air volume (VAV) system (direct expansion coil and gas heating coil). Table 1 lists more information about the model.

Figure 1 Prototypical Three-story Office building

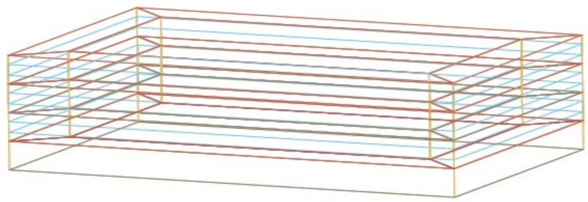


Table 1 Relevant Features of Prototypical Building Model

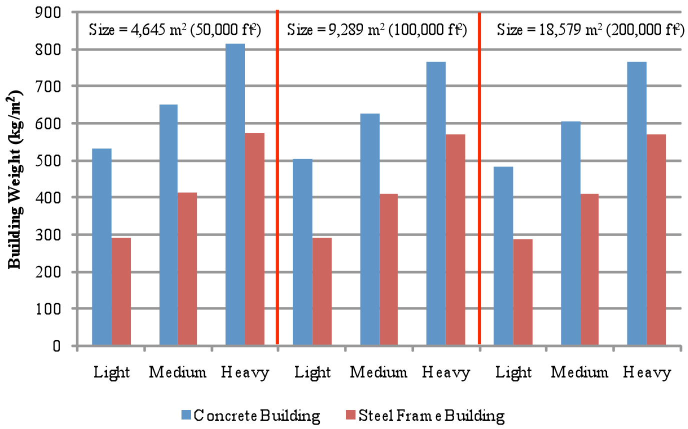
	Input Information
Building Dimensions	Variable with constant aspect ratio (1.5)
Building Envelope	Building construction meets the requirement of Title 24-2005 except thermal mass. Building thermal mass varies by scenario.
Window-to-Wall Ratio	0.38 for each side of the building model
DX Coil	Rated COP under low-speed and high-speed operation are 4.2 and 3.0 respectively. Airflow and capacity are auto-sized by EnergyPlus.
Supply Fan	Variable volume. Total efficiency is 0.63 and static pressure is 600 Pa.
Zone Temperature Setpoints	75 °F (23.9 °C) during the cooling period

Building Envelope

Based on the building envelope criteria for non-residential buildings in California, two types of exterior walls are selected to represent different thermal masses. The window-to-wall ratio is 0.38 for each side of the prototypical building model. The thermal performance of the glazing system also meets the U-value and solar heat gain coefficient requirements for climate zones in California. The thickness of the wall insulation is used to change the U-value to comply with the building envelope requirements for different climate zones in California.

The size of the building is changed by varying length and width of the building while maintaining a constant aspect ratio (1.5). The internal thermal mass is represented as three levels: light, medium and heavy. Six-inch standard wood is used to model the internal thermal mass in the prototypical EnergyPlus model. Different internal thermal mass levels are represented in terms of the percentage of total floor area covered by internal furnishings. External thermal mass levels vary with the size and type of building construction. Figure 2 shows the comparison of the average weight of concrete and steel-framed buildings with different thermal mass levels. The average weight of the building varies linearly with increased internal thermal mass and with the external thermal mass. Taking a 50,000 ft^2 (4,645m^2) concrete building as an example, the average weight of the building with low, medium and high thermal mass levels is 108.6 lb/ft^2 (531.2 kg/m^2), 133.4 lb/ft^2 (652.7 kg/m^2) and 166.5 lb/ft^2 (814.7 kg/m^2), respectively.

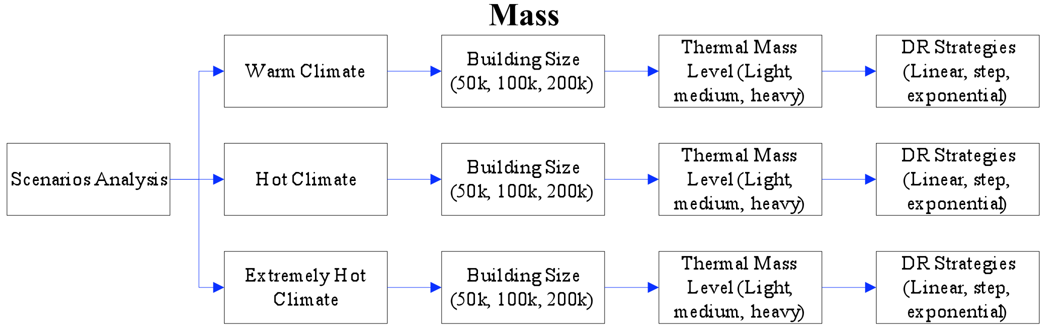
Figure 2 Comparisons of Average Weight between Concrete and Steel Frame Buildings



Methodology

Figure 3 shows the summary of scenarios considered to evaluate the range of peak demand savings for commercial buildings with different size and thermal mass levels. In addition to the above-mentioned building sizes and thermal mass levels, we consider climate zones and different DR control strategies. There are a total of 162 simulation runs, 81 runs for the concrete building and 81 runs for the steel frame building.

Figure 3 Summary of Scenarios Analysis for Commercial Buildings with Thermal Mass



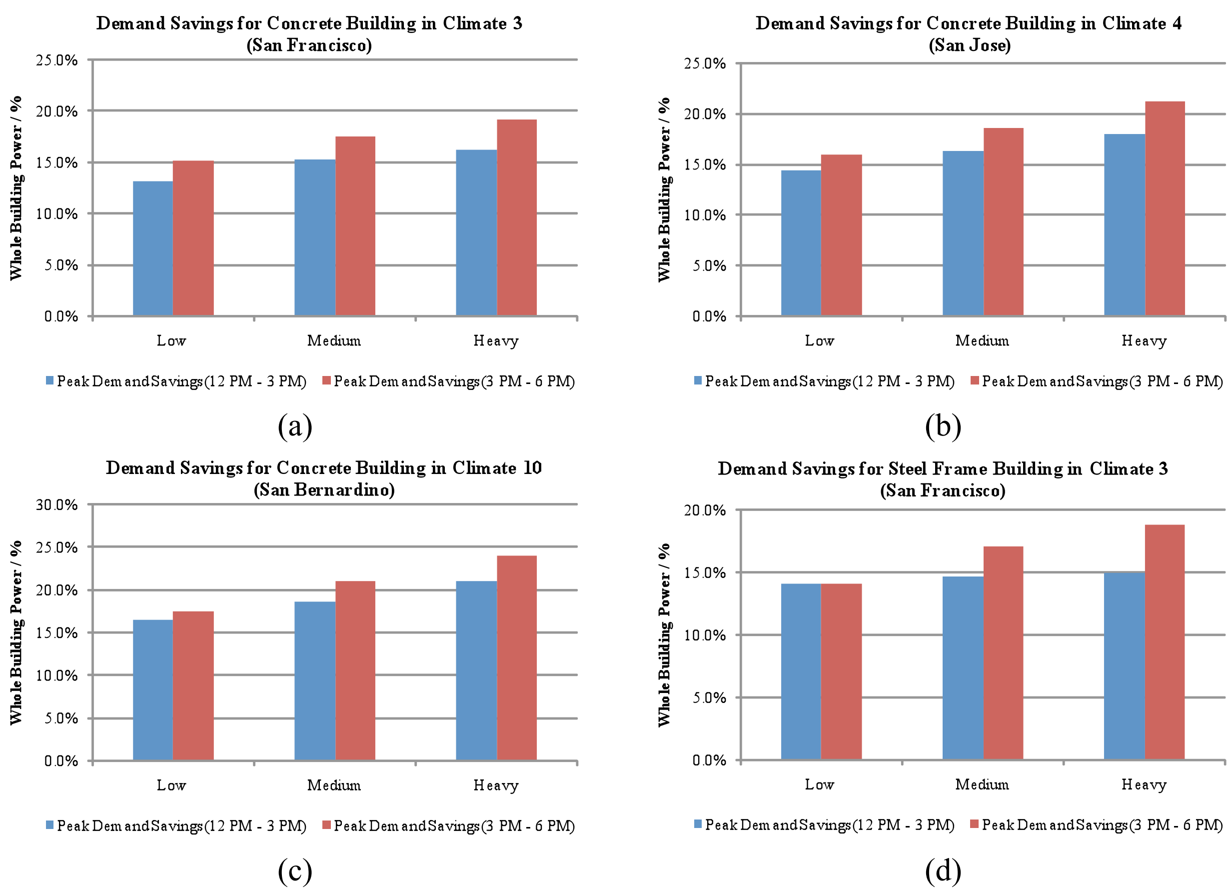
As part of the scenario analysis, three control strategies are modeled to study the impact of DR control strategies on demand savings. The zone cooling temperature setpoints are 75°F (23.9°C) for normal operation. The first strategy is termed "pre-cooling with linear temperature set up". From 6 a.m. to 12 p.m., the zone temperature setpoints are reduced by 2°F (1.1°C). From 12 p.m. to 6 p.m., the zone temperature setpoints rise linearly to 80°F (26.7°C). After 6 p.m., the zone temperature setpoints are rolled back to normal operation. The second strategy is termed "pre-cooling with two-step temperature set up". The zone temperature setpoints are the same as the first strategy during the pre-cooling period. Then the setpoints are increased to 77°F (25.0°C) at 12 p.m. and remain there until 3 p.m., when the setpoints are again reset, to 79°F (26.1°C), for the duration of the afternoon (until 6 p.m.). The third strategy is termed "pre-cooling with exponential temperature set up". This strategy has the same pre-cooling controls as the linear strategies, though the zonal temperature setpoints increase exponentially in the afternoon (i.e., the temperature is continuously increasing). The zonal temperature setpoints are 76.7°F (24.8°C), 78.5°F (25.8°C), 79.2°F (26.2°C), 79.6°F (26.4°C), 79.8°F (26.6°C), 80°F (26.7°C) for each hour from 12 p.m. to 6 p.m.. For all three strategies, the HVAC system turns off after 6 p.m. allowing zone temperature float.

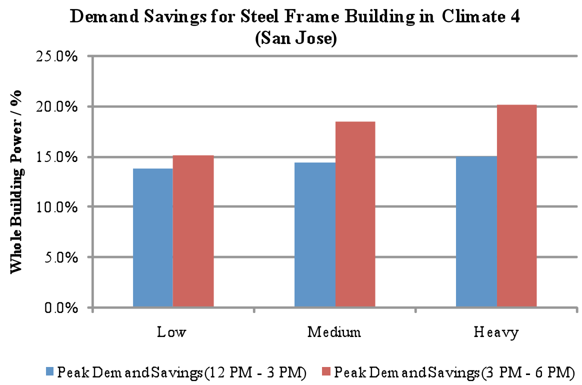
Results

Effects of Thermal Mass Levels

The results (Figure 4) present the role of mass in reducing the peak power. High thermal mass offers the greatest potential for higher demand savings due to the high thermal storage during the pre-cooling period. For the 50,000 ft^2 (4,645m^2) concrete building, the peak demand power can be reduced by 24% using the "pre-cooling with exponential zonal temperature set up" control strategy. Since the capacity of thermal storage from thermal mass in buildings with low thermal mass is limited, the pre-cooling period can be shorter compared to medium and high thermal mass buildings, thus reducing the need for increased energy consumption during the pre-cooling period. Ideally, the optimal duration and depth of the pre-cooling period can be determined through simulation of employing various pre-cooling strategies in various scenarios.

Figure 4 Demand Savings for Concrete and Steel Frame Buildings in Climates 3, 4, and 10





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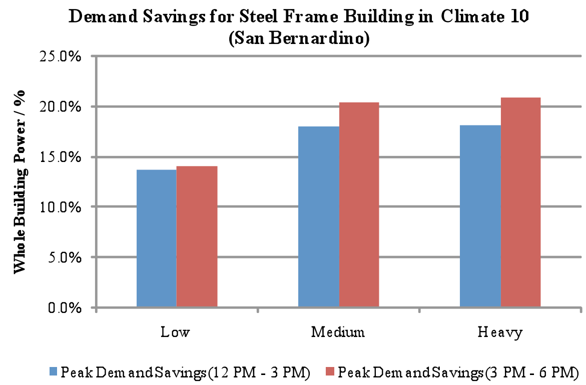


(f)

Climate Effects

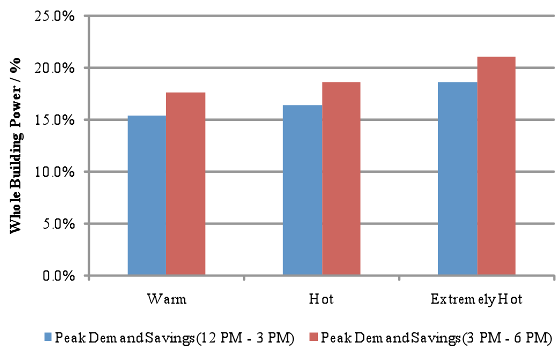
In this study, California climate zones 3, 4 and 10 are selected to represent warm, hot and extremely hot climates for the scenario analysis to evaluate the impact of the climate on the peak demand savings. The weather data used in the models are TMY3 (Typical Meteorological Year) weather files available within DRQAT. Table 2 shows the design day maximum dry-bulb temperatures and cooling degree days of each climate zone. Although the design day temperatures in climate zones 3 (San Francisco) and 4 (San Jose) are very similar, the amount of cooling degree days of climate zone 4 is almost 5 times that of climate zone 3.

Table 2 Design Day Data and Degree Days of Climate Zones

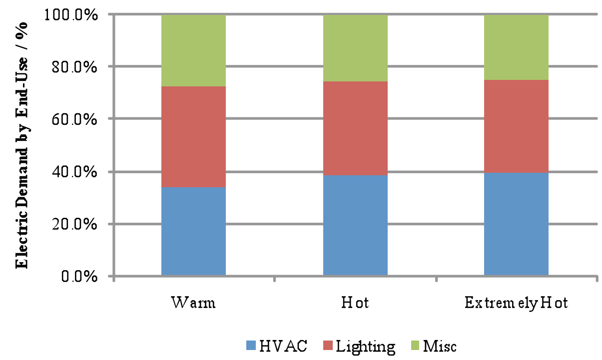
	Climate Zone 3 (San Francisco)	Climate Zone 4 (San Jose)	Climate Zone 10 (San Bernardino)
Summer Design Day Max. Dry-Bulb Temperature	27.8°C (82°F)	29.4°C (85°F)	37.8°C (100°F)
Cooling Degree Days (base 80 °F)	108	574	1937

The concrete building with medium thermal mass is discussed here as an example to illustrate the impact of different climates on the demand savings from the "pre-cooling with exponential zonal temperature set up" control strategy. For a warm climate (San Francisco), the peak demand savings can be up to 17.5%. In contrast, the results for the extremely hot climate (San Bernardino) show that the peak demand savings increase to 21.0%. For buildings in the extremely hot climate, the higher demand of the HVAC system (relative to the HVAC demands in cooler climate zones) explains the greater demand savings. As shown in Figure 5 (b), the HVAC system accounts for 34.1% of the electric demand in a warm climate compared to 39.8% in an extremely hot climate. The results follow the similar trends for other building under the same scenarios.

Figure 5 Impact of Different Climate Conditions on Demand Savings (a) and Electric End-Use Demand (b) for Concrete Buildings with Medium Thermal Mass



(a)



(b)

Effects of Demand Response Control Strategies

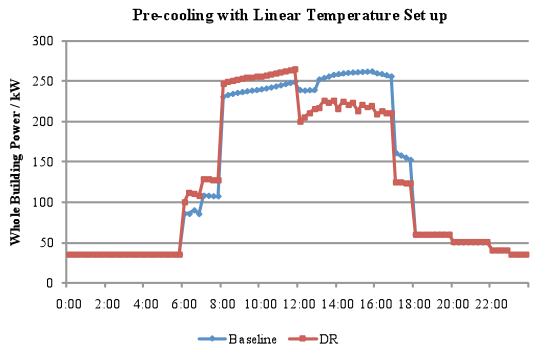
Figure 6 illustrates the effect of various DR control strategies on the whole building power profile. The results presented consider a medium size concrete building with medium thermal mass in a hot climate zone. For the same building base model, the control strategy "pre-cooling with exponential temperature set up" achieves the greatest peak demand savings and flattens the demand power profile, as well. Although the zone temperature setpoints rise to 26.7°C (80°F) at the end of the peak period for all of the control strategies, the greatest demand savings and average energy savings are achieved with the "pre-cooling with exponential temperature set up" strategy.

Summary of Simulation Results and Field Test Data

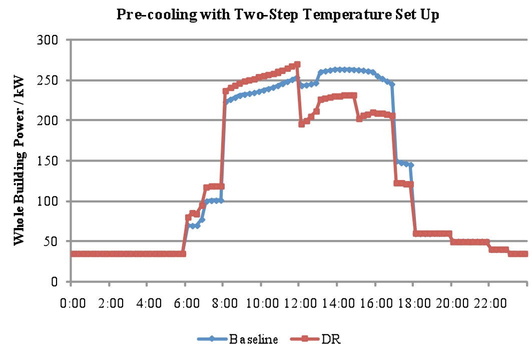
Table 3 presents the simulation results of the scenario analysis for concrete commercial buildings employing the optimal DR strategy, "pre-cooling with exponential temperature set up". For medium-sized commercial buildings in an extremely hot climate zone, the peak demand savings range from 18.0% to 20.3%, assuming a medium thermal mass level. Notice that the larger building achieves less demand savings in all climates, as the average weight of the thermal mass is inversely proportional to building size as shown in Figure 2.

Table 4 shows the field test results that were used to verify the simulation results for selected scenarios (Xu et al. 2008). For test site #1 described in Table 4, the peak demand savings ranged from 19.0% to 24.0% when the "pre-cooling with exponential temp reset" strategy was employed. For test site #2, the peak demand decreased by 15-19% under the same DR control strategy. Moreover, the peak demand of test site #2 was reduced by 14-15% and 20-30%, in warm and extremely hot weather conditions, respectively, which agreed with the simulation results. The simulated peak demand savings and the field test results appear to be in agreement.

Figure 6 (a) Pre-cooling with Linear Temperature Set Up, (b) Pre-cooling with Two-Step Temperature Set Up and (c) Pre-cooling with Exponential Temperature Set Up



(a)



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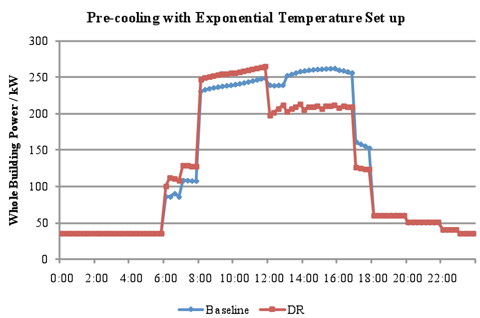


(c)

Table 3 Scenarios for Concrete Commercial Buildings Using Optimal DR Strategy

Climate in Summer	Thermal Mass Level	4,645 m^2 (50,000 ft^2)		9,289 m^2 (100,000 ft^2)		18,579 m^2 (200,000 ft^2)	
		Demand Savings (12 PM-3 PM)	Demand Savings (3 PM-6 PM)	Demand Savings (12 PM-3 PM)	Demand Savings (3 PM-6 PM)	Demand Savings (12 PM-3 PM)	Demand Savings (3 PM-6 PM)
Warm	Low	13.2%	15.2%	12.4%	13.4%	12.5%	13.2%
	Medium	15.3%	17.5%	15.1%	16.6%	15.1%	16.0%
	Heavy	16.2%	19.2%	17.1%	18.4%	17.2%	18.6%
Hot	Low	14.3%	15.9%	13.4%	14.9%	12.7%	14.1%
	Medium	16.3%	18.6%	15.6%	18.1%	14.9%	17.6%
	Heavy	18.0%	21.2%	17.2%	20.9%	19.2%	20.5%
Extremely Hot	Low	16.5%	17.5%	15.5%	16.6%	14.8%	15.9%
	Medium	18.6%	21.0%	18.0%	20.3%	17.5%	19.8%
	Heavy	21.0%	24.0%	20.3%	23.4%	20.0%	22.9%

To evaluate the accuracy of the DRQAT model for predicting the whole building peak demand, the simulation result is compared to California Commercial End-Use Survey (CEUS) and other eleven field test buildings (Yin et al. 2010) as shown in Figure 7. The CEUS whole building peak demand is based on survey data. It represents the non-coincident peak load of approximately 14,909,000 ft^2 of large office buildings in an extremely hot climate zone. The simulation results from DRQAT are lower than field test data and CEUS, likely due to the assumed lighting densities and HVAC system efficiencies. In DRQAT, the prototypical office building model meets the requirements of Title 24-2005, which requires lower lighting density and more efficient HVAC systems than the older buildings considered in both CEUS and the field tests. Thus, the whole building peak demand is lower.

Table 4 Field Tests of Peak Demand Savings for in Extremely Hot Climates

Test Site	General Information	DR Control Strategies	Outside Temp	Peak Periods	WBP% Max	WBP% Ave
#1	8,081 m^2 (87,000ft^2), typical office building in Visalia, CA	Pre-cooling with linear temp reset	37.2°C (99°F)	12 pm - 3 pm	13%	7%
				3 pm - 6 pm	25%	19%
		Pre-cooling with exponential temp reset	38.9°C (102°F)	12 pm - 3 pm	24%	16%
				3 pm - 6 pm	23%	14%
		Pre-cooling with exponential temp reset	38.9°C (102°F)	12 pm - 3 pm	19%	10%
				3 pm - 6 pm	20%	16%
#2	9707 m^2 (104500 ft^2), typical office building in San Bernardino, CA	Pre-cooling with linear temp reset	40.0°C (104°F)	12 pm - 3 pm	19%	6%
				3 pm - 6 pm	15%	13%
		Pre-cooling with exponential temp reset	40.0°C (104°F)	12 pm - 3 pm	16%	10%
				3 pm - 6 pm	17%	11%
		Pre-cooling with exponential temp reset	43.3°C (110°F)	12 pm - 3 pm	20%	9%
				3 pm - 6 pm	30%	23%
		Pre-cooling with exponential temp reset	28.9°C (84°F)	12 pm - 3 pm	15%	10%
				3 pm - 6 pm	14%	10%

Note: WBP% refers to the savings from the whole building power.

Comfort Analysis

As shown in Figure 8, The zone temperature for a heavy mass building is 0.4°C (0.7°F) lower than that of a light mass building by employing the same control strategy "pre-cooling with exponential temperature set up". Moreover, the highest zone temperature of the heavy mass building is 0.4°C (0.7°F) lower than the 26.6°C (79.9°F) setpoint, which indicates that this building has further demand savings potential, similar to the field test results in 2007 (Xu et al. 2008). In that study, although the building setpoints were at 25.0°C (77°F) on one extremely hot day, the return air temperature on a typical exponential temperature reset test day was never higher than 24.4°C (76°F).

Zone comfort is evaluated based upon the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) thermal comfort indices (Fanger 1970) available within the simulation. The thermal comfort range is normally considered as -0.5 < PMV < +0.5 and PPD < 10%. During the pre-cooling period for the heavy mass building, the worst case of the simulated PPD and PMV indices are 10.5% and -0.5 due to the pre-cooling strategy and low outside air temperature, which are slightly out of the thermal comfort range. During peak hours, the calculated PPD and PMV indices indicate that the occupants perceived the room as comfortable, both in the baseline scenario and when the DR control strategy was employed in a heavy mass building. The low mass buildings show more difficulty maintaining comfort during a DR period.

Figure 7 Comparisons between Field Test Buildings, CEUS, and DRQAT Model

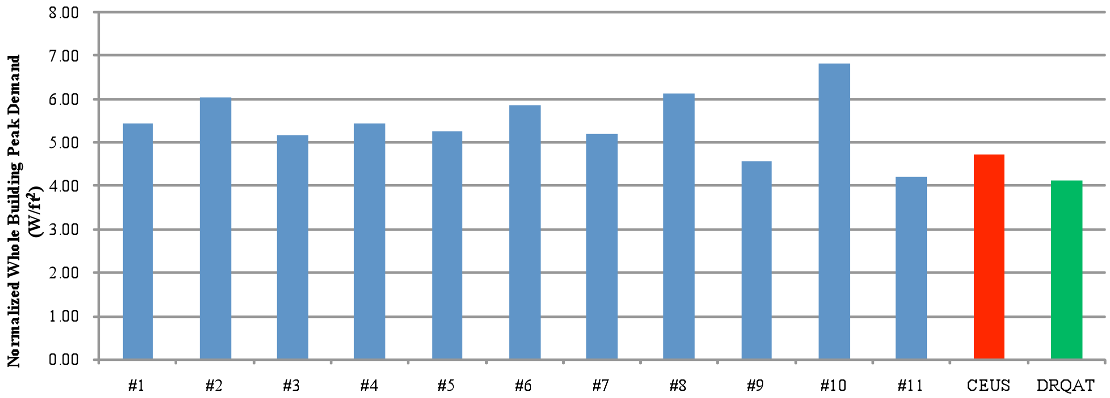
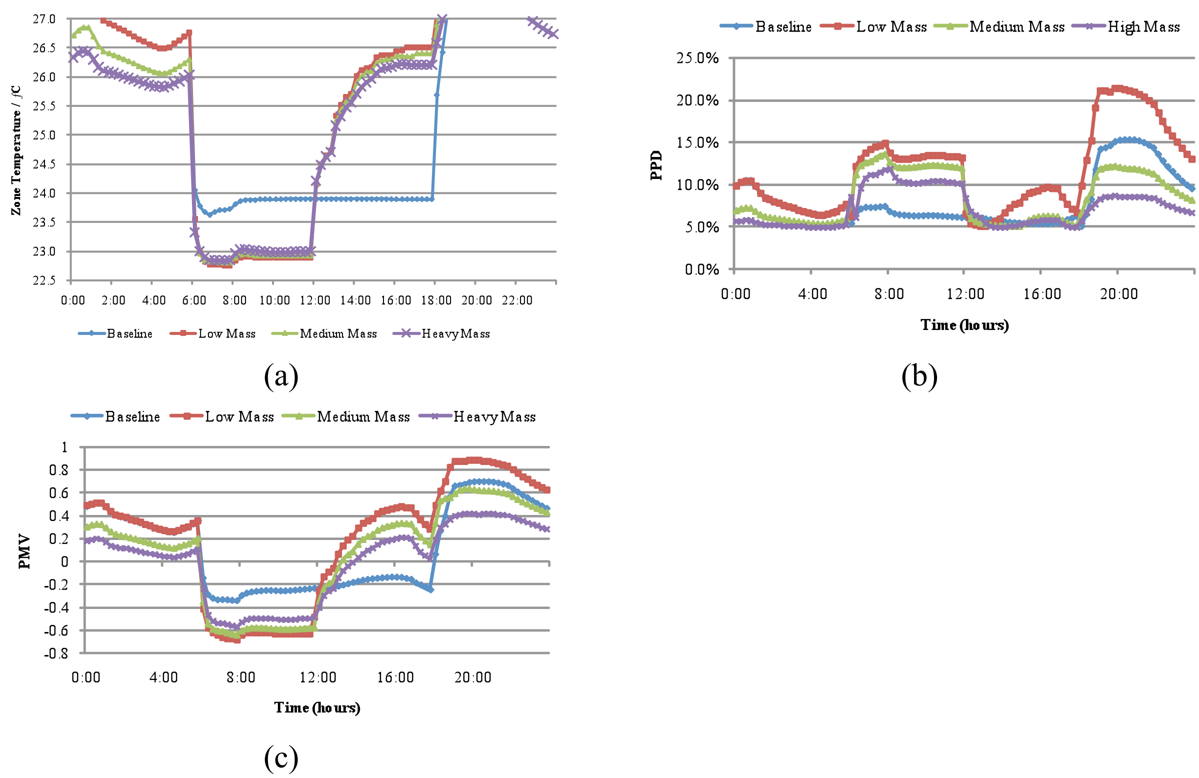


Figure 8 Comparison of Zone Temperature (a), PPD (b), and PMV (c) for Different Mass Conditions under Pre-Cooling with Exponential Temperature Set Up Strategy



Economic Analysis

A set of existing electricity rates are used to evaluate the impact of the DR strategies on economic savings for different thermal mass and climate conditions. Based on peak demand power and locations, Pacific Gas and Electric Company (PG&E)'s rate schedule E19T – TOU/PDP is used for medium-size commercial customers with registered demand of 200 kW -

500 kW. Peak Day Pricing (PDP) is a new rate plan proposed by PG&E to improve the reliability of the electrical grid and reduce greenhouse gas emissions. Under PDP, the design basis for rates is 12 PDP calls per year. PDP event days are generally triggered by high temperature, corresponding to the 12 hottest days in DRQAT.

Table 5 presents detailed rate information. The total energy cost includes the customer charge, energy charge, monthly demand charge and other delivery and generation charges. There is another charge for the PDP rate program, PDP Adder, which applies to usage between 2 p.m. to 6 p.m. on Peak Days. Table 6 shows the economic cost savings for medium thermal mass buildings under optimal DR control strategy "pre-cooling with exponential temperature set up" in the summer. The results in Table 6 indicates that customers can save up to 45% on their energy bill *before* PDP adder charges using the "E19T-PDP" rate program (rather than the "E19T-TOU" rate program), due to the lower on-peak demand charge. However, the total bill savings are much less significant because the PDP adder charges on peak days offset the monthly demand charge savings from PDP rate program. Table 6 also indicates that the customers receive nearly 20% PDP adder savings from the optimal DR control strategy. In fact, if participants want to benefit economically at all from the PDP program, Table 6 shows that they are *required* to drop and shift energy use away from these event days and times. It is important to note that this type of building should run the DR control strategies on most days, not just PDP days, in order to achieve both energy and demand savings in the summer season.

Table 5 Summer Rate Programs for Medium Commercial Customers

Rate Schedule	Energy Charge ($/per kWh)			Demand Charge ($/kW)			PDP Adder ($/per KWh)
	On-Peak	Mid-Peak	Off-Peak	On-Peak	Mid-Peak	Maximum	Peak Days
E19T - TOU	0.10436	0.08231	0.06913	9.16	2.07	4.24	-
E19T - PDP	0.10436	0.08231	0.06913	3.49	0.79	4.24	1.2
PG&E: Peak hours (12 p.m. to 6 p.m.), off-peak hours (9:30 p.m. to 8:30 a.m.)							

Table 6 Energy and Demand Savings from Proposed Control Strategy

Rate Program	Warm		Hot		Extremely Hot	
	Demand Charge ($)	Energy Charge ($)	Demand Charge ($)	Energy Charge ($)	Demand Charge ($)	Energy Charge ($)
E19T – TOU	22,357	33,517	23,982	35,534	25,240	36,730
E19T – PDP	12,277	33,380	13,091	35,389	13,850	36,567
E19T – PDP Adder	-	12,180	-	12,805	-	14,074
PDP Adder With DR	-	10,158	-	10,487	-	11,217
Total (E19T-TOU)	55,874		59,516		61,970	
Total (E19T-PDP)-DR	55,815		58,967		61,634	
Bill Savings ($)	59		549		336	

Conclusions and Recommendations

A series of prototypical building demand response control strategy scenarios are modeled to evaluate the peak demand savings opportunities for commercial buildings in California. These scenarios can help guide building operators to evaluate the potential for peak demand and economic cost savings using various DR control strategies. This study also quantified the thermal mass levels for concrete and steel frame buildings in terms of average weight. The impact of different scenarios on the demand savings are summarized here.

- **Thermal mass levels**: As expected, the peak demand savings rise with increased building thermal mass. The savings increases due to thermal mass changes are virtually identical in concrete and steel frame buildings. The thermal storage capacity of a building's thermal mass is limited, so the pre-cooling period should be optimized by comparing the demand power profile with the charging time during the pre-cooling period.
- **Climate Conditions**: For a concrete building with medium thermal mass, the whole building electrical peak demand can be reduced by up to 15.2% and 21.0% during peak hours in warm and extremely hot climate zones, respectively. Steel framed buildings follow similar trends. Both the simulation results and field test data indicate that the peak demand savings increase in hotter climate zones.
- **DR Control Strategies**: A variety of temperature reset profiles were evaluated: "pre-cooling with linear temperature set up," "pre-cooling with two-step temperature set up," and "pre-cooling with exponential temperature set up." These control strategies were modeled to illustrate the effect of DR control strategies on peak demand savings. The "pre-cooling with exponential temperature set up" control strategy achieved the greatest peak demand savings and the flattest afternoon electric load shape.
- **Zone Comfort**: The objective of the pre-cooling and DR control strategy is to achieve the maximum peak demand savings while maintaining the occupancy comfort. The reset of the zonal temperature setpoints. In this study, the zone temperature for a heavy mass building is 0.4°C (0.7°F) lower than that of a light mass building in an extremely hot climate. Moreover, the maximum zone temperatures in the afternoon are 0.4°C (0.7°F) lower than the setpoints. Similar conditions were observed in previous field tests (Xu et al. 2008).
- **Economic Analysis**: In this study, the customers achieve little cost savings from the PDP rate coupled with the DR strategy. While on the side of the electricity provider, they can benefit from the reduced peak demand power for not increasing the capacity of the electricity plant. The results of the economic analysis illustrate the cost savings for different sized commercial buildings with thermal mass and help customers to achieve maximum cost savings based on their demand power profiles. These results can also guide utility providers in optimizing electricity tariff design.

Several case studies have validated the simulated peak demand savings. Observations from field tests also confirm that peak demand savings increase as warm, hot, and extremely hot climate zones are considered. In future work, the duration (hours) and the depth (°F or °C) of the pre-cooling strategies will be optimized via scenario analysis. The prototypical model will also be modified to include different building vintages within each climate zone. The simulation results will be recalibrated to ensure the prototypical models more accurately reflect reality.

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